NAVSHIPS 0967-155-5010
STANDARDS

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13900 N.W. SCIENCE PARK DRIVE · PORTLAND, OREGON 97229

AUGUST 1964
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6446

MODEL

SR 1010

Instruction Manual

RESISTANCE TRANSFER STANDARD

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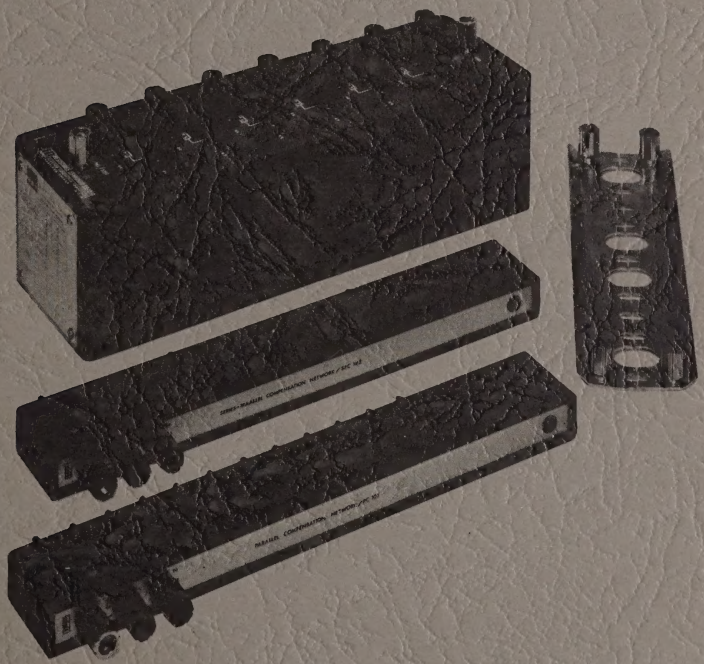

SERIAL NUMBER: _____

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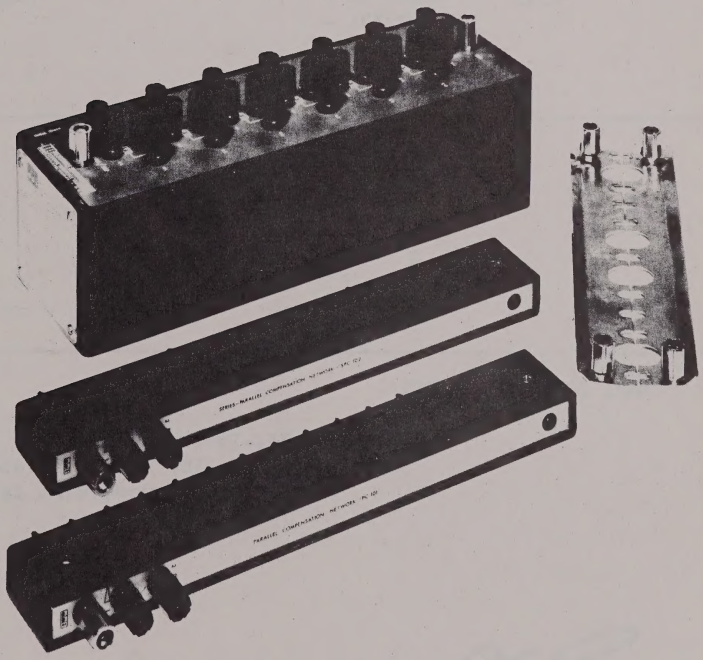

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CONTRACT OR PURCHASE ORDER	SHIPS APPLICABLE	QUANTITY OF MANUALS	QUANTITY OF EQUIPMENT	BUILDING YARD
NObs 4871	T-AGM-6 & T-AGM-7	42	2 - 10Ω Units 2 - 1K Units 2 - 10K Units	Avondale Shipyards, Inc.

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It is hereby certified that NAVSHIPS 0967-155-5010 to be provided under Contract NObs 4871 has been approved by the approval data shown above.

A. E. Page
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Project Apollo Reentry Ships
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SECTION I

DESCRIPTION AND SPECIFICATIONS

1.1 DESCRIPTION

Each MODEL SR 1010 RESISTANCE TRANSFER STANDARD is a resistance box containing twelve nominally equal precision resistors. SR 1010 boxes are available in various resistance values.

There are three basic ways of using a Model SR 1010, depending upon the accuracy required. In many applications, the resistor adjustment accuracy is high enough that the resistors can be assumed to have exactly their nominal values. For higher accuracy, certified calibration data can be used to correct the resistance values. For the ultimate accuracy in a laboratory having a high-accuracy one ohm reference standard, a set of SR 1010 boxes can be used to transfer calibration from the one ohm reference to the entire chain of resistance measuring equipment and standards in the laboratory with an accuracy at the time of calibration much better than the long-term accuracy to which any of the equipment could be certified.

Each MODEL SR 1010 RESISTANCE TRANSFER STANDARD has a calibration chart attached to it, giving the measured deviation of each resistor from its nominal value. The chart also includes the calculated average deviations of resistor groups for use in series, parallel and series-parallel groups. The ESI calibration data supplied is directly traceable to standards certified by the National Bureau of Standards. Blank calibration charts are available for subsequent calibrations. The excellent stability and unusually low temperature coefficient of the resistors used in the SR 1010 assure the maintenance of high accuracy between calibration periods and over normal temperature ranges.

The design of the MODEL SR 1010 RESISTANCE TRANSFER STANDARD and its accessories facilitates the transfer of resistance calibration from one resistance level to another. The series, parallel and series-parallel connections of resistor groups in an SR 1010 to give resistance values of 0.1, 1 and 10 times the individual resistor value is particularly useful in calibrating a set of SR 1010's to a short-term accuracy much better than any long-term certification. A laboratory having one or more Thomas-pattern one ohm resistors as its reference standard can use a set of SR 1010 boxes to calibrate measurements over a wide resistance range to very nearly the same accuracy as that of its one ohm reference standard.

The resistors in an SR 1010 are permanently connected in series. The provision of two binding post terminals at each junction allows accurate four-terminal measurement of any resistor or series group of resistors. Accessories are available for parallel and series-parallel connections. A pair of shorting bars, ESI Model SB 103, is used to connect any number of resistors in parallel or a group of nine resistors in series-parallel. Two different compensation networks, ESI Models PC 101 and SPC 102, are used to eliminate loss of accuracy at the lower resistance levels in making four-terminal measurements of ten resistors in parallel and nine resistors in series-parallel. As a result of the special design of the four-terminal junctions between binding posts and resistors, and the use of the parallel and series-parallel compensation networks, the actual values of four-terminal series, parallel and series-parallel resistor groups will agree with their values calculated from individual resistor values to better than ±0.1 microhm.

The SR 1010 owes its high accuracy and stability to the precision resistors used. The resistors are unifilar-wound on specially processed mica cards, and use a modern alloy resistance wire which has excellent stability, extremely low temperature coefficient and negligible thermal emf to copper. All the resistors in an SR 1010 are wound from the same spool of wire in order to yield the best temperature coefficient and stability matching between resistors. Each resistor is carefully built and inspected to insure maximum control of quality. Resistors for use in Model SR 1010's are selected for minimum temperature coefficient and given a rigorous accelerated aging treatment. The complete resistance transfer standard is given additional stabilization treatment, followed by an extended series of tests to ensure that every SR 1010 conforms to the highest standards of quality.

1.2 SPECIFICATIONS

MODEL SR 1010

RESISTANCE VALUES: Twelve equal four-terminal resistors connected in series. Standard Values: 1, 10 or 100 ohms; 1, 10 or 100 kilohms per step. Values required for 242A system calibration: 10 ohms, 1 kilohm, 100 kilohms.

CALIBRATION TRANSFER ACCURACY WITH PARALLELING COMPENSATION NETWORK: 100 to 1 transfer
±(1 ppm + 0.1 microhm at parallel value)
10 to 1 transfer
±(1 ppm + 1 microhm at series-parallel value)

INITIAL CALIBRATION CHART ACCURACY: ±10 ppm (traceable to National Bureau of Standards)

INITIAL ADJUSTMENT ACCURACY OF RESISTORS: ±20 ppm, matched within 10 ppm

LONG-TERM STABILITY OF RESISTORS: Resistance will remain within ±50 ppm of nominal value for more than one year.

CALIBRATION CONDITIONS: 23°C, four-terminal resistance measurements

TEMPERATURE COEFFICIENT OF RESISTORS:

100 ohms and higher, ±5 ppm/°C, matched within 3 ppm/°C
10 ohms and lower, ±15 ppm/°C, matched within 5 ppm/°C

POWER COEFFICIENT OF RESISTORS FOR TYPICAL MEASUREMENT DUTY CYCLE:

100 ohms and higher, ±0.1 ppm/mw/resistor
10 ohms and lower, ±0.3 ppm/mw/resistor

POWER RATING: 1 watt per step or 5 watts distributed over ten resistors

BREAKDOWN VOLTAGE: 1500 volts peak to case

DIMENSIONS: 12.2" long, 4.4" wide, 4" deep.

WEIGHT: 3-1/4 lbs. net

STANDARD SR 1010 VALUES:
PER STEP

(R) Value - Per Step		1Ω	10Ω	100Ω	1k	10k	100k
One Resistor Alone	Maximum Milliamperes	1000	320	100	32	10	3.2
	Maximum Volts	1	3.2	10	32	100	320
10 Resistors in Parallel (R/10)	Maximum Milliamperes	7100	2300	710	230	71	23
	Maximum Volts	0.71	2.3	7.1	23	71	230
10 Resistors in Series (10R)	Maximum Milliamperes	710	230	71	23	7.1	2.3
	Maximum Volts	7.1	23	71	230	710	2300*

*Do not exceed 1500 peak volts to case

MODEL SB 103 SHORTING BARS

FUNCTION: A pair of shorting bars used to connect any number of resistors of a MODEL SR 1010 RESISTANCE TRANSFER STANDARD in parallel or nine of its resistors in a series-parallel arrangement.

EFFECTIVE RESISTANCE AND ACCURACY: See COMBINED FUNCTIONAL SPECIFICATIONS.

RESISTANCE: End to end: approximately 100μ ohms/bar.

MAXIMUM CURRENT: 10 amps/bar

MODEL PC 101 PARALLEL COMPENSATION NETWORK

FUNCTION: Used in addition to an SB 103 pair for the four-terminal parallel connection of ten resistors in an SR 1010 to yield the same resistance as the value calculated from individual four-terminal resistor measurements.

EFFECTIVE RESISTANCE AND ACCURACY: See COMBINED FUNCTIONAL SPECIFICATIONS.

RESISTOR MATCHING: Matched to ±0.05%

MAXIMUM CURRENT: 2 amps

BREAKDOWN VOLTAGE: 1500 volts to case

MODEL SPC 102 SERIES-PARALLEL COMPENSATION NETWORK

FUNCTION: Used in addition to an SB 103 pair for the four-terminal series-parallel connection of nine resistors in an SR 1010, to yield the same resistance as the value calculated from individual four-terminal resistor measurements.

EFFECTIVE RESISTANCE AND ACCURACY: See COMBINED FUNCTIONAL SPECIFICATIONS.

RESISTOR MATCHING: Matched to ±0.05%

MAXIMUM CURRENT: 2.0 amps

BREAKDOWN VOLTAGE: 1500 volts to case

COMBINED FUNCTIONAL SPECIFICATIONS:

Resistor grouping	Ten resistors in parallel	Nine resistors in series-parallel	Ten resistors in series
Nominal value (relative to individual resistor value R)	0.1R	R	10R
Four-terminal measurement	Resistance added to value calculated from individual resistor values (value and tolerance in microhms)		
With SB 103 and PC 101 or SPC 102	0±0.1	0±1	
With SB 103 alone	50±10	200±40	
With no accessories			0±10
Two-terminal measurement			
With SB 103	150±30	300±60	
With no accessories			300±60

SECTION II

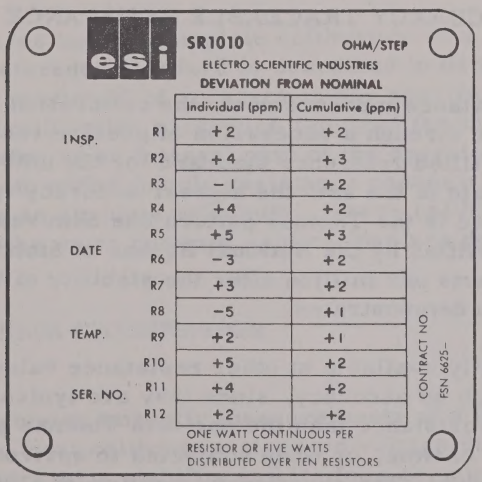
OPERATING INSTRUCTIONS

2.1 BASIC OPERATIONS

2.1.1 USING THE CALIBRATION CHART

The calibration chart on the end of each SR 1010 gives resistance calibration data for individual resistors and groups of resistors in the SR 1010, in terms of their deviation from nominal value, expressed in parts per million. These values are based on four-terminal measurements; two-terminal measurements must be corrected for the connection resistances listed in the specifications and discussed in Section 2.2 (Connections).

A sample calibration chart is shown in Figure 2.1.1.



	Individual (ppm)	Cumulative (ppm)
R1	+2	+2
R2	+4	+3
R3	−1	+2
R4	+4	+2
R5	+5	+3
R6	−3	+2
R7	+3	+2
R8	−5	+1
R9	+2	+1
R10	+5	+2
R11	+4	+2
R12	+2	+2

FIG. 2.2.1

The first column gives the measured deviation of each resistor from its nominal value. The second column gives the cumulative average of the deviation figures in the first column, rounded to the same number of significant figures as the first column. For example, to the right of R7, the figure in the first column is the measured deviation of R7 from nominal, while the figure in the second column is the calculated average deviation of resistors R1 through R7.

The cumulative average deviation in the second column calibrates any series, parallel or series-parallel connection of the corresponding group of resistors in which the power divides equally among all the resistors in the group. For example, the first nine resistors in a one ohm per step box can be connected in series for a nominal value of nine ohms, in parallel for one-ninth of an ohm, or in series-parallel for one ohm; the actual value of each of these three alternate connections will be exactly the same number of parts per million away from the nominal value for that connection.

The calibration chart data supplied initially with each SR 1010 is traceable to the National Bureau of Standard with the specified accuracy under the stated laboratory environmental conditions. A set of SR 1010's can be easily recalibrated relative to any one ohm reference standard, using the procedures described in Section IV.

2.1.2 HIGH-ACCURACY TRACEABLE RESISTANCE MEASUREMENTS

In precision resistance measurement, the calibration of any resistor must be traceable through a succession of precise resistance comparisons to a certified reference standard for the unit of resistance. At the present state of the art, the highest-accuracy type of resistance reference standard is the Thomas pattern one ohm resistor. These resistors are certified by the National Bureau of Standards to an accuracy of ±2 parts per million after the stability of the particular resistor has been demonstrated.

Standards presently available at other resistance values cannot be certified to as high an accuracy, since they are typically somewhat less constant in resistance than the one ohm Thomas pattern over extended periods of time, or when subjected to environmental changes or mechanical shock. The short-term stability of a precision resistor in a laboratory environment, however, is typically much better than its long-term calibration accuracy. The accuracy of a calibration

certificate must reflect this possible long-term instability, but a fresh calibration at the time of use may be far more accurate. Thus the laboratory equipped to trace all of its measurements to one ohm reference standards can calibrate its entire chain of resistance measuring equipment and resistance standards over a wide range of values to a short-term calibration accuracy much better than the accuracy to which such equipment could be certified for use over a long period of time or after transportation from one laboratory to another.

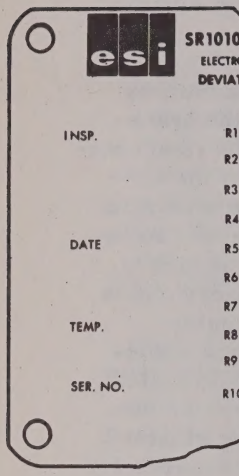
A set of SR 1010 boxes is particularly useful for such high-accuracy calibration, since the SR 1010 is particularly designed for the transfer of calibration from one resistance level to another. This is accomplished by calibrating an SR 1010 at one resistance level and then reconnecting its resistors to yield a different resistance value known to the same accuracy. The comparisons at each resistance level can be made at a one-to-one resistance ratio, ensuring maximum accuracy. Thus the only certified resistance standards which a laboratory needs to maintain are its one ohm reference standards. The traceable calibration of other standards over a wide range of resistance values can be accomplished through the use of a set of SR 1010 RESISTANCE TRANSFER STANDARDS and a one-to-one Kelvin comparison bridge or double ratio set, yielding a higher accuracy than could be obtained by shipping the other standards to the National Bureau of Standards for certification.

The procedures for the complete calibration of a set of SR 1010's from a one ohm reference standard is described in detail in Section IV. For the absolute maximum of accuracy in any specific calibration, those parts of the calibration procedure required for that application should be incorporated as an integral part of the operating procedure at the time of use, in order to hold resistance changes with time or ambient conditions to an absolute minimum. These calibration transfer procedures for the more common applications are described in Section 2.3.

2.1.3 DIVIDER CALIBRATION

To make precision linearity measurements of a voltage divider it is necessary to first calibrate a standard voltage divider. Due to its excellent short term stability and its four-terminal construction which makes it simple to calibrate, the ESI MODEL SR 1010 is ideal for use as such a standard voltage divider.

The following outlines the procedure for calibrating the SR 1010 as a voltage divider with ten equal steps, using the data given on its calibration chart. If the calibration chart has not been verified recently refer to Section 4.3.3 (Calibration of Individual Resistors).



	A Deviation of Individual Resistors from Nominal	B Deviation of Individual Resistors from Average (ppm)	C Cumulative Sum of B (ppm)	D Linearity Deviation at Tap (ppm)
	Individual (ppm)		0.0	0.0
R1	+2	+0.4	+0.4	+0.0
R2	+4	+2.4	+2.8	+0.3
R3	-1	-2.6	+0.2	+0.0
R4	+4	+2.4	+2.6	+0.3
R5	+5	+3.4	+6.0	+0.6
R6	-3	-4.6	+1.4	+0.1
R7	+3	+1.4	+2.8	+0.3
R8	-5	-6.6	-3.8	-0.4
R9	+2	+0.4	-3.4	-0.3
R10	+5	+3.4	0.0	0.0

10 | 16 Sum

1.6 Average

FIG. 2.1.3

1) Add up the deviations from nominal of the first ten resistors of the SR 1010.

   These are the values given in the first column of the calibration chart on the end of the SR 1010, see Figure 2.1.3 column A.

2) Divide this sum by ten to find the average deviation.

3) Subtract the average deviation from each of the ten individual deviations.

   See Figure 2.1.3 column B.

4) Starting with the first deviation from average, sum up all the deviations from average through each of the ten taps. For example the cumulative sum for the third tap would be the sum of the first, second and third deviations from average, for the example shown in Figure 2.1.3 this would be 0.4+2.4-2.6= 0.2.

See Figure 2.1.3 column C. The last figure in this column should always be zero.

5) Divide each of the cumulative sums by ten to get the linearity deviation at each tap.

See Figure 2.3.1 column D.

The calibrated SR 1010 can now be used as a standard divider for calibrating other dividers. The following outlines the procedure for comparing the two.

6) Connect the SR 1010 and a microvoltmeter to the divider to be calibrated as shown in Section 2.2.4.

7) Adjust the end correcting potentiometers as described in Figure 2.2.4b.

8) Connect the microvoltmeter between corresponding taps on the SR 1010 and divider to be calibrated, and measure the deviation of the output of the unknown divider from the output of the SR 1010 at each tap.

The linearity deviation of the unknown divider will be

$$L^r_{unk} = \frac{V_{\mu v}}{E_{in}} + L^r_{std}$$

where:

L^r_{unk} is the linearity deviation of the unknown divider at the rth tap.

$V_{\mu v}$ is the reading of the microvoltmeter.

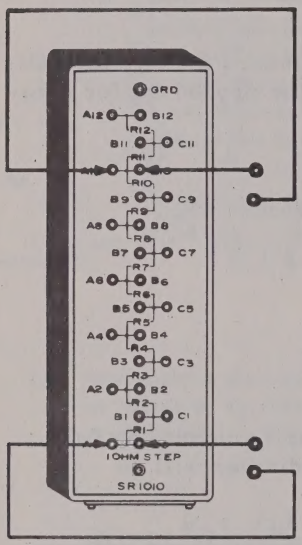
E_{in} is the voltage applied to the input of the dividers.

L^r_{std} is the linearity deviation of the SR 1010 for corresponding tap. (Column D)

2.2 CONNECTIONS

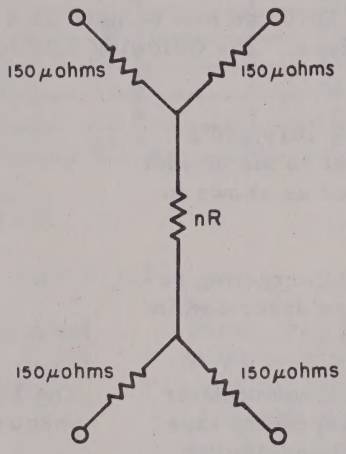
2.2.1 SINGLE RESISTOR OR SERIES GROUP

The SR 1010 was designed for use as a four-terminal resistor. The four connections are made to the two pairs of binding posts at either end of any of the resistors. The resistors are internally connected in series; to connect to n resistors in series it is only necessary to connect to the opposite ends of the 1st and nth resistors, see Figure 2.2.1a.



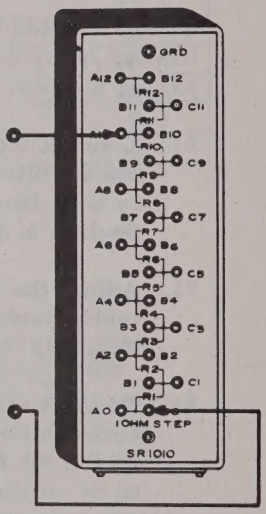
Four-terminal connection of ten resistors in series.

FIG. 2.2.1a



Equivalent circuit of n resistors in series.

FIG. 2.2.1b



Two-terminal connection of ten resistors in series.

FIG. 2.2.1c

The junction design that connects the resistors in series and to the binding post terminals is such that it contributes less than one microhm resistance to that of a four-terminal measurement of the individual resistors.

The SR 1010 may also be used as a two-terminal resistor; however, the calibrated four-terminal value must be corrected for the terminal resistance. Due to the design of the terminals at the end of each resistor it makes no difference which one is used for a two-terminal measurement. The resistance contributed by these terminals will be within ±0.06 milliohms of the resistance measured between the pair of terminals connected to the same end of any resistor, (about 0.3 milliohms), see Figure 2.2.1d.

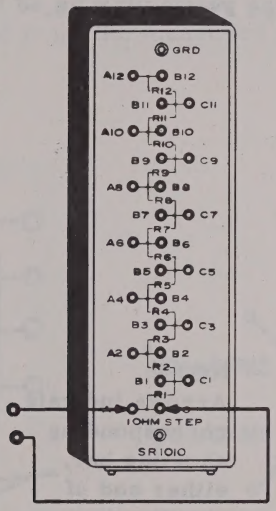
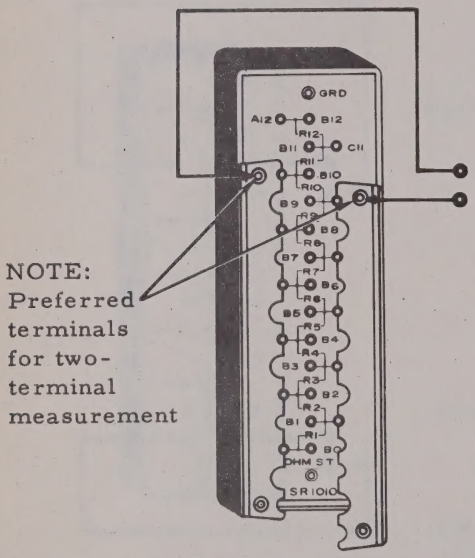


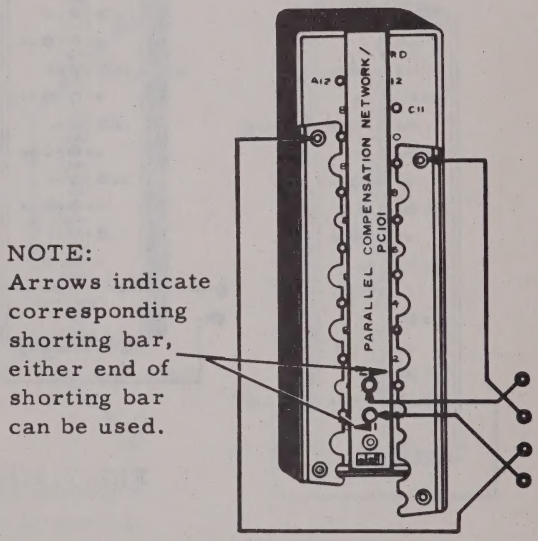
FIG. 2.2.1d

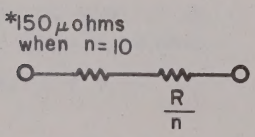
2.2.2 PARALLEL GROUP OF RESISTORS

Any number of resistors of a SR 1010 can be connected in parallel by means of shorting bars (ESI MODEL SB 103 or equivalent), see Figure 2.2.2a. For individual resistors of less than one hundred ohms, the paralleling leads and contact resistance may cause significant errors.

In connecting ten resistors in parallel, these errors can be essentially eliminated by use of a special compensation network for making four-terminal parallel connections (ESI MODEL PC 101 PARALLEL COMPENSATION NETWORK), see Figure 2.2.2b.

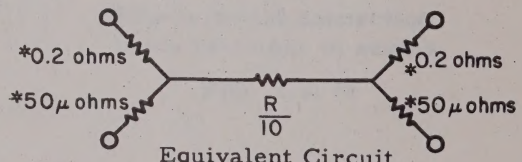



NOTE:
Arrows indicate corresponding shorting bar, either end of shorting bar can be used.
PARALLEL COMPENSATION NETWORK / PC101
A12
C11



Equivalent Circuit

FIG. 2.2.2a



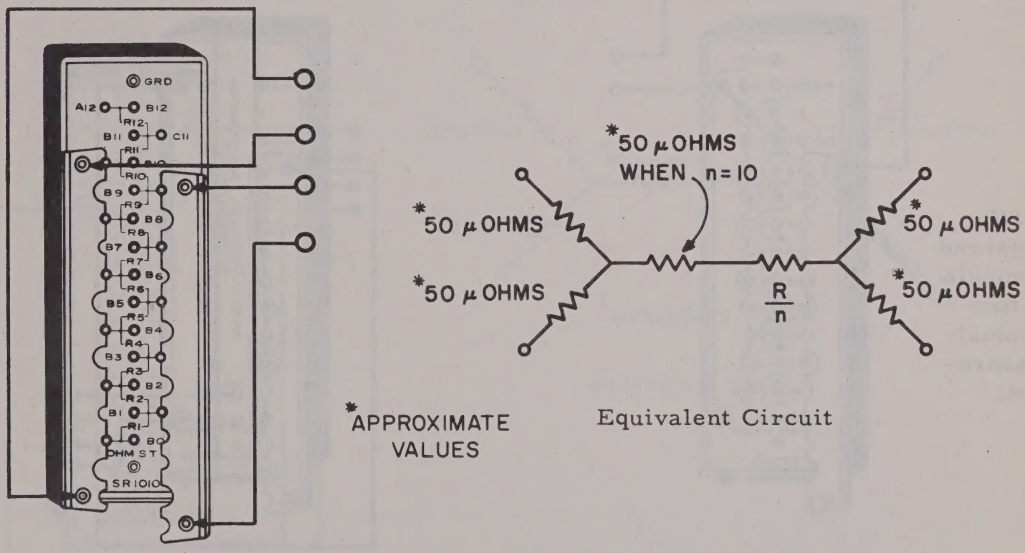
Equivalent Circuit

*APPROXIMATE VALUES

FIG. 2.2.2b

It should be noted that the resistance in series with the terminals to the compensation network is considerably higher than that in series with the terminals to the shorting bars, see Figure 2.2.2b. When connecting this paralleled group of resistors and compensating network to a bridge or ratio set care should be taken to connect these higher resistance terminals where they will least affect the accuracy of the measurement.

A simplified four-terminal parallel connection of any number of resistors can be made using only the shorting bars as shown in Figure 2.2.2c. This places a small connection resistance in series with the paralleled resistance. However, since there will be several contacts in parallel it will be a fairly stable and reproducible resistance and can be subtracted from the measured value, see Figure 2.2.2c.

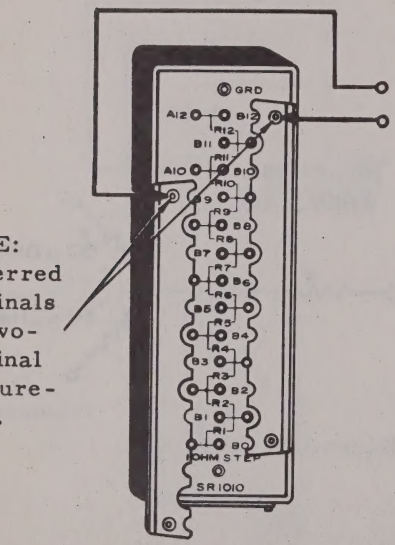


Simplified four-terminal parallel connection.

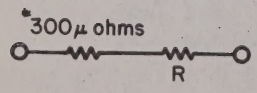
FIG. 2.2.2c

2.2.3 SERIES-PARALLEL GROUP OF RESISTORS

In addition to the series and parallel connections, series-parallel connections of the SR 1010 are also possible. With this method nine resistors, three parallel groups of three resistors in series, may be used to form a stable resistor equal in value to the individual resistors in the string. The ESI MODEL SB 103 SHORTING BARS can be used for this type of connection also, see Figure 2.2.3a. For individual resistors of less than one hundred ohms resistance, the paralleling leads and contact resistance may cause significant errors. These errors can be essentially eliminated by use of a special compensation network for making four-terminal series-parallel connections (ESI MODEL SPC 102 SERIES-PARALLEL COMPENSATION NETWORK). Such a network is shown connected to a SR 1010 in Figure 2.2.3b.



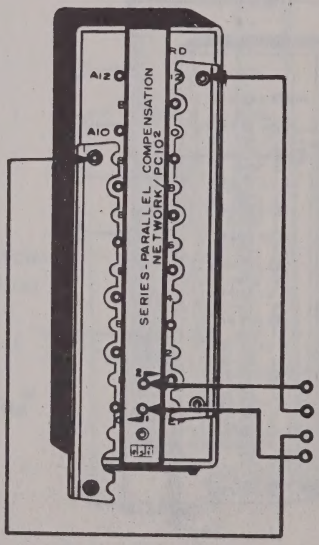
NOTE: Preferred terminals for two-terminal measurement.

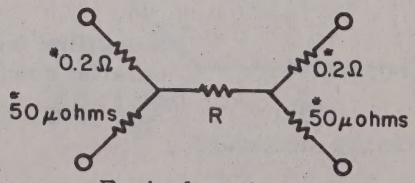


Equivalent Circuit

*APPROXIMATE VALUES

FIG. 2.2.3a



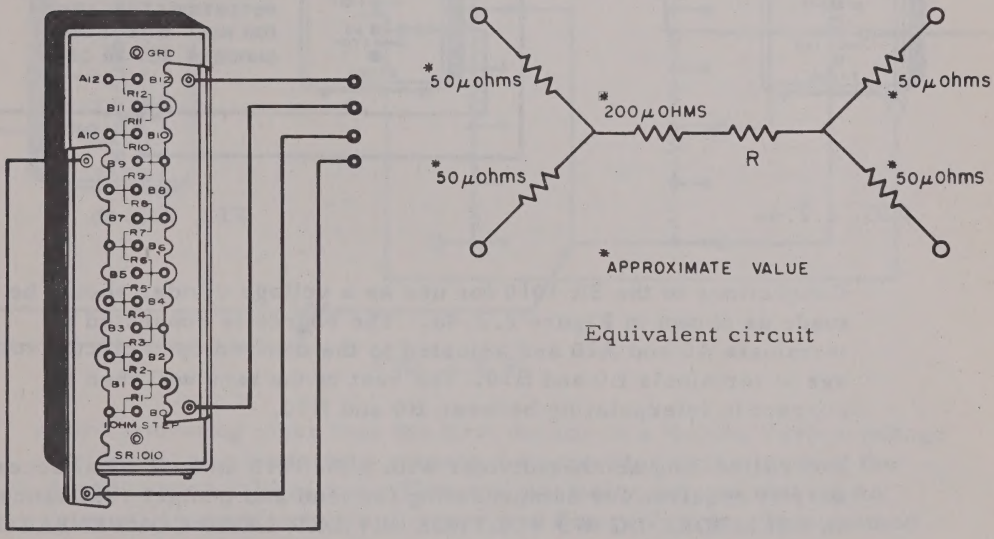


Equivalent Circuit

FIG. 2.2.3b

It should be noted that the resistance in series with the terminals to the compensation network is considerably higher than that in series with the terminals to the shorting bars, see Figure 2.2.3b. When connecting this paralleled group of resistors and compensating network to a bridge or ratio set care should be taken to connect these higher resistance terminals where they will least affect the accuracy of the measurement.

A simplified four-terminal series-parallel connection can be made using only the shorting bars as shown in Figure 2.2.3c. This places the connection resistance of the shorting bars in series with the series-paralleled resistance. However, since there will be several contacts in parallel it will be a fairly stable and reproducible resistance and could be subtracted from the measured value, see Figure 2.2.3c.



Simplified four-terminal series-parallel connection.

FIG. 2.2.3c

2.2.4 DIVIDER CONNECTIONS

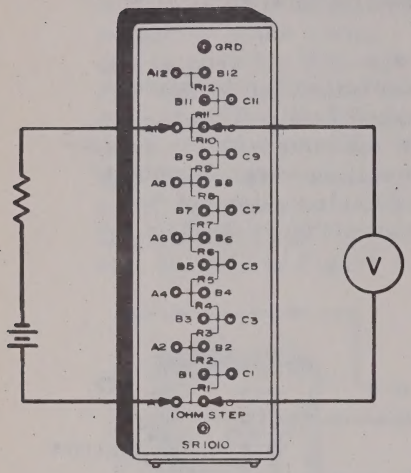


FIG. 2.2.4a

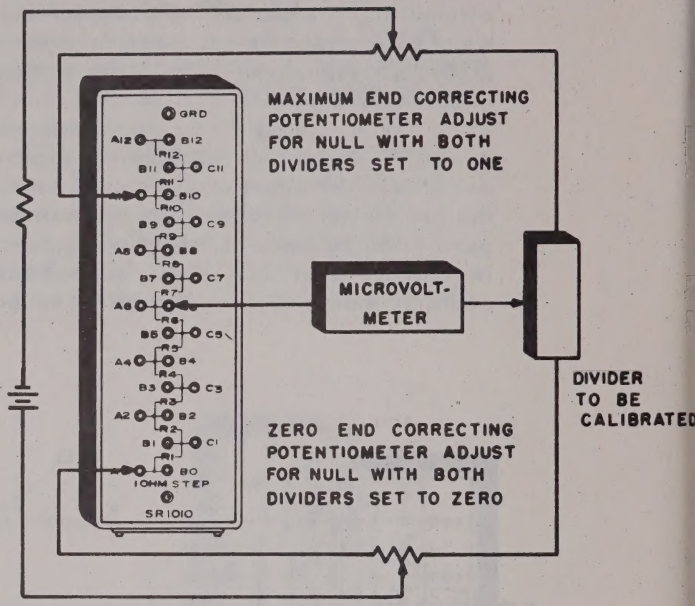


FIG. 2.2.4b

Connections to the SR 1010 for use as a voltage divider should be made as shown in Figure 2.2.4a. The source is connected to terminals A0 and A10 and adjusted to the desired open circuit voltage at terminals B0 and B10. The rest of the taps will then be correct in interpolating between B0 and B10.

For calibrating another divider with a SR 1010 an additional accessory is required for compensating for lead and contact resistances, an ESI MODEL LC 875 VOLTAGE DIVIDER LEAD COMPENSATOR or equivalent is recommended. The lead compensator is connected between terminals B0, B10 and the input of the divider to be calibrated, see Figure 2.2.4b. With the detector connected between A0 and the minimum end of the divider to be calibrated the lead compensator is adjusted for a detector null. Change the detector connections to A10 and the maximum end of the detector to be calibrated and adjust the lead compensator for a detector null. The divider to be calibrated may then be accurately compared to the SR 1010 at integral multiples of one tenth the full scale voltage.

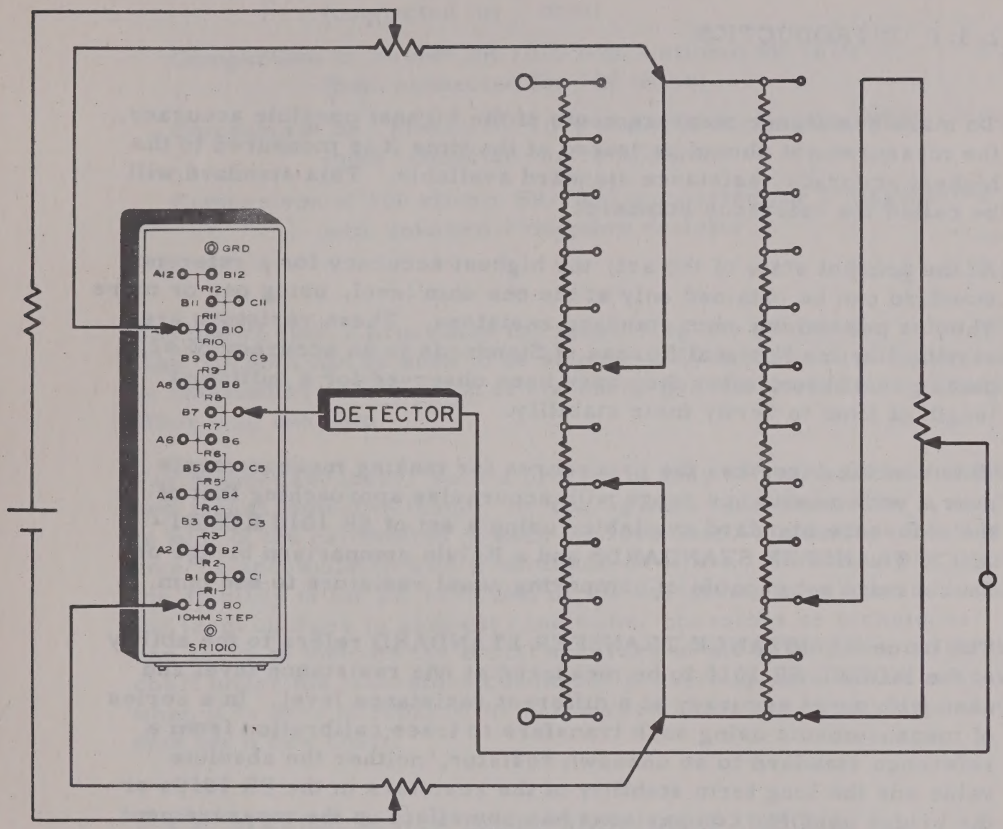


FIG. 2.2.4c

For calibrating other than the first decade of a Kelvin-Varley voltage divider it is necessary to connect the generator to the input of the decade under calibration. This will normally require making an internal connection to the divider, see Figure 2.2.4c. This method gives a complete, high accuracy calibration of the whole Kelvin-Varley divider, including all lead and switch resistances.

2.3 HIGH ACCURACY CALIBRATION TRANSFER

2.3.1 INTRODUCTION

To make resistance measurements of the highest possible accuracy, the measurement should be traced at the time it is measured to the highest accuracy resistance standard available. This standard will be called the reference standard.

At the present state of the art, the highest accuracy for a reference standard can be obtained only at the one ohm level, using one or more Thomas pattern one ohm standard resistors. These resistors are certified by the National Bureau of Standards to an accuracy of ±2 parts per million, after they have been observed for a sufficient length of time to verify their stability.

This section describes the procedures for making measurements over a wide resistance range with accuracies approaching that of the reference standard available, using a set of SR 1010 RESISTANCE TRANSFER STANDARDS and a Kelvin comparison bridge or double ratio set capable of comparing equal resistors to one ppm.

The name RESISTANCE TRANSFER STANDARD refers to the ability of the MODEL SR 1010 to be measured at one resistance level and used with equal accuracy at a different resistance level. In a series of measurements using such transfers to trace calibration from a reference standard to an unknown resistor, neither the absolute value nor the long term stability of the resistors in the SR 1010s or the bridge used for comparisons has any effect on the measurement accuracy. The burden of calibration accuracy and long-term stability is placed on the reference standard alone; the concern with the rest of the system need be only with its short-term stability during the period of a few minutes required to complete the measurement. With careful operating technique in a normal laboratory environment, each step in such a series of measurements can be accurate to one or two ppm.

In making such a chain of measurements, one of the advantages of using a set of ten resistors connected as in the SR 1010 is that a 100 to 1 transfer in resistance level can be made at each measurement, minimizing the accumulation of errors. For example, the limits of error in measuring a one megohm resistor might be assumed as follows:

Certified accuracy of 1 ohm standard	2 ppm
Comparison of 1 ohm standard with 10 ohm SR 1010 (connected for 1 ohm)	2 ppm
Comparison of 10 ohm SR 1010 with 1 kilohm SR 1010 (both connected for 100 ohms)	2 ppm
Comparison of 1 kilohm SR 1010 with 100 kilohm SR 1010 (both connected for 10 kilohms)	2 ppm
Comparison of 100 kilohm SR 1010 (connected for 1 megohm) with unknown 1 megohm resistor	2 ppm
Total	10 ppm

The use of such a procedure for measuring any resistance value other than one ohm can be seen to be substantially more accurate than could be obtained by certification of standards presently available at values other than one ohm.

For highest accuracy, such a procedure may be repeated each time a new measurement is made. If, during such measurements, a record is kept of the calibration of each SR 1010 used, a quantity of data will soon be accumulated with a minimum of effort. This data will indicate the stability of the SR 1010 and/or the variations in calibration resulting from changes in ambient conditions, operators or techniques. It can serve to indicate the actual accuracy of the data on the calibration chart under the laboratory conditions prevailing, and it will indicate when it is time to replace the calibration chart and supply dependable data for a new chart.

2.3.2 MAKING EQUAL RESISTANCE COMPARISONS

The comparison of like resistance values can be made independent of the absolute accuracy and long-term stability of the comparison bridge by using either an interchange or a substitution method. A direct-reading double ratio set, such as the ESI MODEL 240 KELVIN RATIO BRIDGE, for making four-terminal comparison measurements with a 1 ppm resolution and short-term stability, should be used for calibration transfer with SR 1010s.

The following outlines the procedure for comparing two resistors by the interchange method:

1) With the standard resistor or previously calibrated SR 1010 connected to the standard terminals of the bridge and the unknown

resistor or SR 1010 to be calibrated connected to the unknown terminals, balance the bridge and determine the deviation of the unknown from the standard. Call this reading d_1.

2) With the unknown resistor connected to the standard terminals and the standard resistor connected to the unknown terminals, balance the bridge and determine the deviation of the standard from the unknown. Call this reading d_2.

3) Calculate $\frac{d_1 - d_2}{2}$ this is the deviation of the unknown resistor from the standard resistor. To obtain the deviation of the unknown resistor from nominal value, add to this calculated value the deviation of the standard resistor from nominal value.

To compare two resistors by the substitution method, connect to the standard terminals of the bridge a working standard resistor of the required value and make two measurements, the first with the standard resistor or previously calibrated SR 1010 connected to the unknown terminals, and the second with the unknown resistor or SR 1010 to be calibrated connected to the unknown terminals. The difference between these two readings will be the difference between the two resistors.

The substitution method is particularly convenient when either the working standard or the bridge ratio can be adjusted to make the bridge deviation dial read deviation from nominal value directly. The procedure is then modified so that when the known resistor is connected to the unknown terminals, the deviation dial is adjusted to its known deviation from nominal value and the working standard or ratio calibration adjustment is used to balance the bridge. When the known resistor is disconnected and the unknown connected to the unknown terminals, the deviation dial at balance will indicate directly the deviation of the unknown resistor from nominal value.

In a series of calibration transfer measurements in which the unknown resistance in one comparison and the known resistance in the next consist of the same group of resistors differently connected, the deviation reading in the first comparison becomes the initial deviation setting for the next measurement. Thus the dial setting serves as a mechanical memory and indicates the actual deviation value through the whole series of measurements, including the final reading on the unknown resistor.

The ESI MODEL RS 925 DECADE RESISTANCE STANDARD makes an excellent adjustable, four-terminal working standard with a 1 ppm resolution at settings of 100 ohms and above. The 100 ohm setting of the RS 925 can be used for measurements by the substitution method

at 1 and 10 ohms if the bridge has ratios of 10 to 1 and 100 to 1. The ESI MODEL 240 KELVIN RATIO BRIDGE provides these ratios, though at somewhat reduced accuracy as a result of sensitivity to lead resistance errors in the connection to the unknown. To retain the full accuracy of the 1 to 1 ratio of the Model 240 bridge for measurements at 1 and 10 ohms, another SR 1010 can be used as a fixed working standard -- use the 1 ohm box as a working standard when calibrating the 10 ohm box, and vice versa.

2.3.3 USING A CERTIFIED RESISTANCE STANDARD

It is necessary to begin any chain of transfer measurements with a very accurately known and highly stable standard resistor. The Thomas pattern one ohm resistor is such a resistor and is recommended for this purpose. These resistors are commercially available and many of them are certified to an accuracy of ±2 ppm per year. In high-accuracy calibration transfer measurements, the Thomas pattern one ohm resistor is used to calibrate the nine-resistor series-parallel configuration of the 1 ohm SR 1010 or the ten-resistor parallel configuration of the 10 ohm SR 1010.

The following suggestions will aid in making measurements at the one ohm level with maximum accuracy:

1) Operate the Thomas pattern resistor in oil in order to minimize its temperature rise with power dissipation and to allow accurate measurement of the resistor temperature. If accurate temperature coefficient data is available for the resistor (α and β terms), a small unstirred pot of oil at room temperature is quite adequate. Measure the oil temperature to an accuracy of ±0.2°C and calculate the value of the resistor at this temperature.

2) To avoid internal heating of the standard and the SR 1010, use reduced input power to the bridge for the initial balance adjustment, then increase power to approximately one half watt (2/3 amp through standard and unknown) for only a few seconds, to make the final accurate balance adjustment. Both the Thomas pattern resistor and the SR 1010 will typically remain constant within 1 ppm for approximately 10 seconds at this power level.

3) When using 1 ohm and 10 ohm SR 1010 boxes, complete their comparison with the reference standard and their use in calibrating higher value SR 1010s in as short a time as possible, in order to

keep all the measurements at as nearly the same temperature as possible. The exact temperature of an SR 1010 in calibration transfer is unimportant, but its temperature must remain sufficiently constant throughout the procedure. This is particularly important with the 1 and 10 ohm boxes, since they have higher temperature coefficients then the higher value boxes.

In changing the connections to the SR 1010, avoid unnecessary handling, in order to minimize temperature changes.

2.3.4 CALIBRATION TRANSFER BETWEEN SR 1010 BOXES

In calibration transfer measurements, the three most commonly used connection configurations for the SR 1010s are ten resistors in parallel, nine resistors in series-parallel, and ten resistors in series, yielding resistance values of 0.1, 1 and 10 times the individual resistor value. It is always preferable to use one of these groups of resistors in preference to any single resistor, in order to minimize temperature rise with internal heating and to take advantage of averaging of temperature coefficients of the various resistors in the box.

The basic absolute resistance calibration of an SR 1010 box is accomplished by accurately measuring any one of these three connection configurations. Once the reference standard or a previously calibrated SR 1010 has been used to calibrate one of these three configurations for a box, the values for all other resistor configurations are obtained by calculation using this value with selected measurements of the resistors in the same box relative to one another or relative to the nine-resistor series-parallel configuration having the same resistance value.

For 1 ppm accuracy in calibrating or using the ten resistor parallel and nine resistor series-parallel configurations, the PC 101 and SPC 102 compensation networks must be used with the 1 ohm and 10 ohm boxes, and with the 100 ohm box unless a correction is made for terminal resistance. The simplified four-terminal connection using the SB 103 shorting bar pair alone is adequate for SR 1010s having values of 1 kilohm per step or higher (see Section 2.2).

The recommended sequence for calibration transfer to the various SR 1010 boxes is as follows:

SR 1010 (ohms/step)	Connection	Number of Resistors	Compared to
1	Series-Parallel	9	One Ohm Reference Standard
10	Parallel	10	
100	Series-Parallel	9	10 ohm per step SR 1010 ten resistors in series
1K	Parallel	10	
10K	Series-parallel	9	1 kilohm per step SR 1010 ten resistors in series
100K	Parallel	10	

2.3.5 CALIBRATION TRANSFER BETWEEN PRINCIPAL CONFIGURATIONS

The majority of calibration transfer applications require the use of only the three principal resistance configurations for the SR 1010 boxes; for these measurements, the individual resistors need never be calibrated. This is the key to both the high accuracy and the extreme simplicity of this transfer technique.

The basic rule relating resistor configurations is that all configurations which use the same group of resistors and distribute the power equally among them have the same deviation from the nominal values for the configurations; this deviation is equal to the average of the deviations of the individual resistors in the group from their nominal value. (This is true to one part in 10^9 for the resistor matching used in SR 1010s).

Thus ten resistors in series will have exactly 100 times the resistance of the same ten resistors in parallel, or nine resistors in series-parallel will have exactly nine times their resistance in parallel, or exactly one ninth of their resistance in series. Thus when a resistor group is calibrated in one configuration and exactly the same group used in another configuration at a different resistance level, no further measurements are necessary and no calculations are required.

To transfer calibration between the ten resistor group and the nine resistor group, the difference between the tenth resistor and the nine-resistor series-parallel configuration must be measured* in order to calculate the average deviations of the two groups.

The formula relating the average deviation of one group to that of the other, to calculate one when the other has been measured, is:

$$d_{av}^{9} - d_{av}^{10} = 0.1\ (d_{av}^{9} - d_{10})$$

in which:

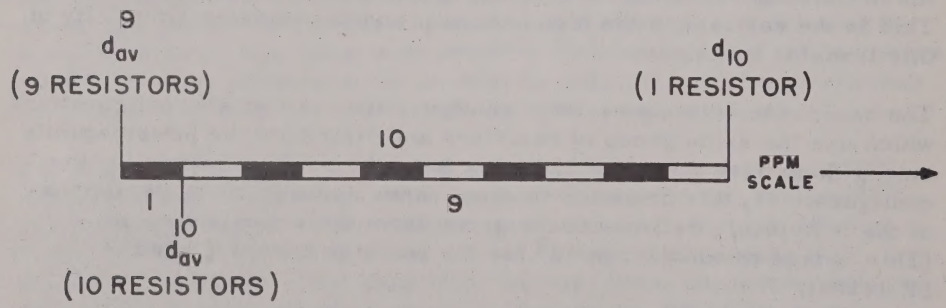
d_{av}^{9} is the average deviation of the nine resistor group from nominal.

d_{av}^{10} is the average deviation of the ten resistor group from nominal.

d_{10} is the deviation of the tenth resistor from nominal.

$(d_{av}^{9} - d_{10})$ is the measured difference between the nine-resistor series-parallel configuration and the tenth resistor.

This formula can be visualized as a weighted average on a diagram as follows:



*For box values requiring the use of the compensation networks, this measurement must be made by the substitution method, rather than the interchange method, since the network must be removed to connect to the tenth resistor for measurement.

Note that the measured difference is multiplied by one tenth; thus if the measurement by the substitution method is accurate to 1 or 2 ppm, the calculated difference between the groups will be correct to 0.1 or 0.2 ppm, which can be considered negligible compared with the accuracy to which the measured group is known.

2.3.6 CALIBRATION TRANSFER TO INDIVIDUAL RESISTORS

To calibrate the individual resistors of a SR 1010 it is recommended that the deviation from nominal of a series or parallel group of ten, or a series-parallel group of nine be determined as accurately as possible by comparison to a known reference standard. Next each of the individual resistors must be compared to a stable working standard to determine their deviations relative to one another. From these relative deviations the average deviation for the group first measured is calculated. The difference of this measured deviation from nominal minus the calculated average deviation is added to each of the individual deviations to determine the deviation from nominal of the individual resistors.

A step by step procedure for calibrating the individual resistors of a complete set of SR 1010s is given in Section 4.3.1 and 4.3.2 and is exemplified in Section 4.3.3.

2.3.7 CALIBRATION OF AN SR 1010 AS A TEN-STEP DIVIDER

Since ratio measurements do not depend upon any absolute resistance standard, no reference standard of resistance is required to calibrate an SR 1010 as a divider. The procedure for calibrating an SR 1010 as a divider with ten equal steps is as follows:

1) Connect a stable working standard, whose nominal value is equal to that of the individual resistors of the SR 1010 to be calibrated, to the standard terminals of the bridge. This standard may be ten resistors in series (or parallel) of the SR 1010 whose resistance per step is one tenth (or ten times) that of the SR 1010 to be calibrated.

2) Measure d_n, the deviation of each of the first ten resistors in the string from that of the standard resistor.

The calibration of the bridge or the accuracy of the working standard need not be considered, only their short term stability is of importance.

3) Calculate the average deviation, d_{av}^{10}, of the ten measured deviations, d_n.

$$d_{av}^{10} = 0.1 \sum_{n=1}^{10} d_n$$

4) Subtract the average deviation, d_{av}, from each deviation d_n.

$$(d_n - d_{av}^{10})$$

5) Sum these differences to each tap and divide by ten to get the linearity deviation at the tap.

$$L_r = 0.1 \sum_{n=1}^{n=r} (d_n - d_{av}^{10})$$

where:

L_r (ratio error) is the linearity deviation at the rth tap. Linearity deviation is defined as the difference between actual tap value and nominal tap value expressed as a proportional part of full scale.

A sample tabular calculation of steps 3), 4), and 5) will be found in Figure 2.1.3.

SECTION III

THEORY

3.1 JUNCTION RESISTANCE EFFECTS

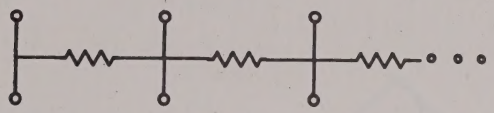


FIG. 3.1a

The series configuration of the SR 1010 TRANSFER STANDARD is shown in Figure 3.1a. The four-terminal resistors can be measured individually or in any series combination. If the measured series resistance is to be equal to the sum of the individual resistor measurements, the junctions must have zero four-terminal resistance. This junction transresistance is zero if a current source connected to any two of the four junction terminals produces zero voltage difference between the other two terminals.

In practice, the junctions do have some transresistance. It is possible to make the resistance very low (much less than 1 microhm) by proper design. For instance, if four terminals are connected to a plane sheet of metal in the configuration shown in Figure 3.1b, two of the terminals will always be on an equipotential line if a current source is connected to the other two terminals.

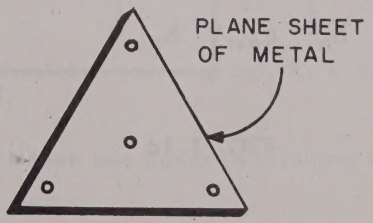


FIG. 3.1b

The tests for a four-terminal point junction are shown in Figure 3.1c. The meter voltages divided by the generator currents are the transresistances for the two connections shown. A third transresistance, shown in Figure 3.1d need not be measured, since it is always equal to the difference between the other two (note that each reading in Figure 3.1c may be either positive or negative; keep this sign when subtracting to calculate third transresistance).

These three transresistances represent the greatest possible resistance measurement error. For the junction in the SR 1010 each of these three resistances is less than 0.5 microhm, causing much less than one ppm error for even a one ohm per step box.

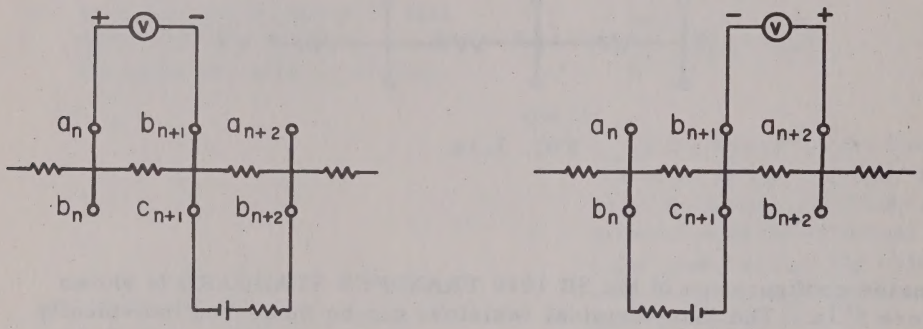


FIG. 3.1c

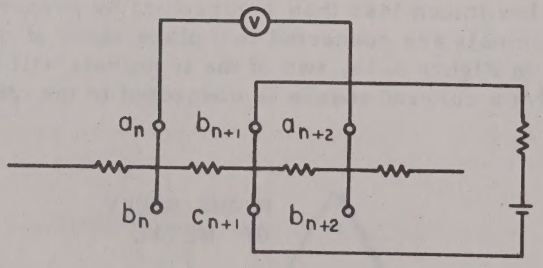


FIG. 3.1d

3.2 INSULATION RESISTANCE EFFECTS

The leakage resistance of the SR 1010 to its case is in excess of 10^{12} ohms. For worst case conditions (twelve one hundred kilohm resistors in series with one end of the SR 1010 tied to its case) the error due to shunt resistance will be less than 1.2 ppm.

If a three terminal measurement is made (the case being the third terminal) and again worst case conditions assumed (twelve resistors in series with all leakage being concentrated from the center point of the series string) the following wye-delta transformation is necessary to determine the resulting error.

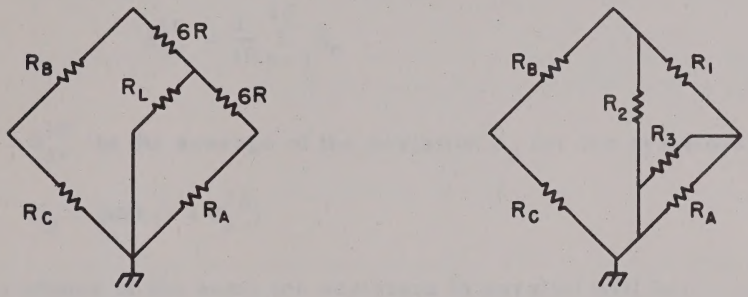


FIG. 3.2

where:

R_A, R_B and R_C are the ratio arms of the bridge.
R is the resistance per step of the SR 1010.
R_L is the leakage resistance from the SR 1010 to its case.

$$R_1 = \frac{36R^2}{R_L} + 12R = 12R\left(1 + \frac{3R}{R_L}\right)$$

R_2 is across the generator or detector so can be neglected.

$$R_3 = 2R_L + 6R$$

For a one hundred kilohm per step box $R_1 = 12R\,(1 + 0.3 \text{ ppm})$ and $R_3 = 2 \times 10^{12}$.

If R_A is no greater than one hundred kilohms the error will not exceed 0.3 ppm.

Since leakage resistance will lower the measured resistance in a two-terminal measurement and increase it in a three-terminal measurement the actual resistance must lie between these two values. This fact can be used as a check to determine the magnitude of the error due to leakage resistance.

3.3 BASIC TRANSFER ACCURACY

To make transfer measurements which do not depend on the absolute accuracy of the transfer standard but only on its short term stability, it is necessary to assume that ten resistors in parallel are exactly equal to one one hundredth of the same ten resistors in series. To see how valid this assumption is let R be the nominal value of the individual resistors and d_n the deviation from nominal of this nth resistor. The value of the nth resistor will then be $R_n = R(1 + d_n)$. The value of the ten resistors in series will be:

$$R_s = \sum_{n=1}^{10} R\,(1 + d_n) = 10R\,(1 + \frac{1}{10} \sum_{n=1}^{10} d_n)$$

$$d_{av}^{10} = \frac{1}{10} \sum_{n=1}^{10} d_n$$

where:

d_{av}^{10} is the average of the deviation d_n for ten resistors.

$$R_s = 10R\,(1 + d_{av}^{10})$$

The resistance of the same ten resistors in parallel will be:

$$R_p = \frac{1}{\sum_{n=1}^{10} \frac{1}{R\,(1 + d_n)}}$$

$$\frac{1}{R(1 + d_n)} = \frac{1}{R}\,(1 - d_n + {d_n}^2 - {d_n}^3 \ldots\ldots)$$

$$R_p = \frac{1}{\sum_{n=1}^{10} \frac{1}{R}\,(1 - d_n + {d_n}^2 \ldots\ldots)}$$

$$R_p = \frac{R}{10} \cdot \frac{1}{1 + \frac{1}{10} \sum_{n=1}^{10} (-d_n + {d_n}^2 \ldots\ldots)}$$

$$R_p = \frac{R}{10}\left(1 + \frac{1}{10}\sum_{n=1}^{10} d_n - \frac{1}{10}\sum_{n=1}^{10} d_n^2 \ldots\ldots\right)$$

$$R_p = \frac{R}{10}\left(1 + d_{av}^{10} - \frac{1}{10}\sum_{n=1}^{10} d_n^2 \ldots\ldots\right)$$

$$R_p \approx \frac{R}{10}\left(1 + d_{av}^{10}\right)$$

The assumption being that $\frac{1}{10}\sum_{n=1}^{10} d_n^2$ is negligible. Since d_n maximum for the SR 1010 is less than 100 ppm d_n^2 will be less than 0.01 ppm which can be neglected, thus the original assumption is quite valid. A similar analysis can be made for the series-parallel connection or any other configuration in which the power divides equally among the resistors.

3.4 FOUR-TERMINAL PARALLELING

The parallel connection of ten four-terminal resistors is shown in Figure 3.4a.

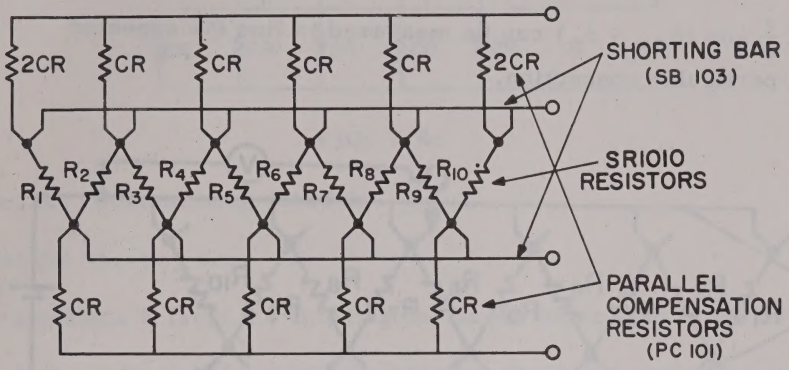


FIG. 3.4a

FIG. 3.4a TEN FOUR-TERMINAL RESISTORS IN PARALLEL

The shorting bar resistance and the resistance from the junctions to the shorting bars should be small. The parallel-compensation resistors should be large compared to the uncertainty in the contact resistances when they are connected and should be proportional to the resistance of the SR 1010 resistors. The two parallel-compensation resistors on the ends are double the others because they connect to one build-up resistor instead of two in parallel.

When several nominally equal resistors are connected in parallel the connection accuracy can be analyzed by assuming all of the compensation resistors except one are equal, and that all of the bus bar resistances except one are zero. At the same time all of the resistors being connected are assumed to be perfect except one. The three imperfect resistors all meet at one of the junctions. Since small first order error effects add linearly the results of this analysis can be extended to determine the connection accuracy. The connection uncertainty is less than:

$$\pm 2\left(\frac{r}{R}\right)(d_{CR} - d_R)$$

where:

r is the greatest bus bar resistance
R is the nominal value of resistors being parallel connected
$(d_{CR} - d_R)$ is the greatest bridge unbalance in terms of resistance deviations of the compensation resistors and the resistors being connected

The values of $\frac{r}{R}$ and $(d_{CR} - d_R)$ can be measured to find the expected accuracy of a particular connection.

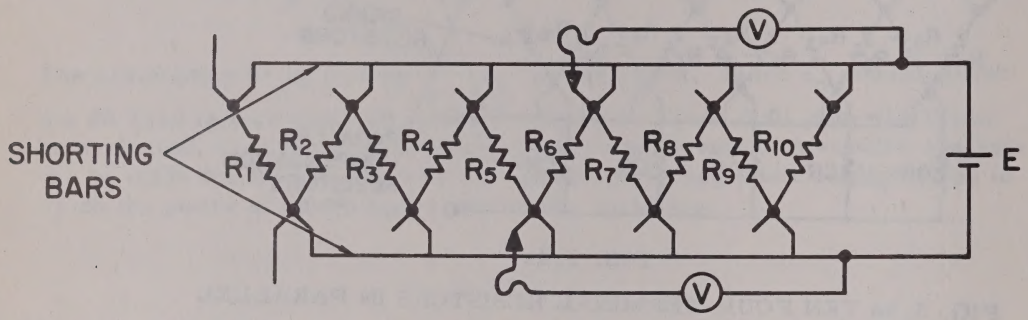


FIG. 3.4b

Connect the shorting bars.

Measure voltage from a point on the bars to the unused terminals, this is the voltage to the junction of adjacent resistors.

Find the maximum difference of values V for each bar.

Use the greatest V difference to calculate $(\frac{r}{R})_{max}$

$$\text{for } r \ll R \qquad \frac{V_{max} - V_{min}}{E} \approx (\frac{r}{R})_{max}$$

The value of $\frac{r}{R}$ can be found by measuring the voltage drops from a point on the bus bars to the junction of adjacent resistors, shown in Figure 3.4b.

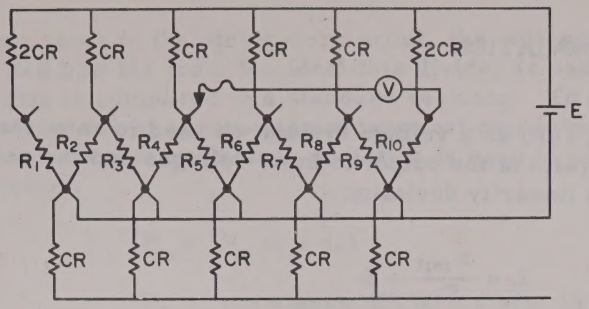


FIG. 3.4c

Connect the compensating network.

Connect the shorting bar.

Supply a voltage E from the shorting bar to the other side of the network.

Measure the voltage V from one unused shorting bar terminal to each of the others.

Change the shorting bar to the other side and repeat.

Find the maximum voltage difference $(V_{max} - V_{min})$ between terminals.

Calculate $(d_{CR} - d_R)_{max}$

$$\left(\frac{V_{max} - V_{min}}{E}\right)\left(2 + \frac{2CR}{R} + \frac{R}{R}\right) = (d_{CR} - d_R)_{max}$$

The bridge unbalance can be measured as shown in Figure 3.4c. The measured values of $\left(\frac{r}{R}\right)_{max}$ and $(d_{CR} - d_R)_{max}$ can be multiplied together and doubled to give an upper bound of the connection error. This usually includes a very substantial safety factor. The same technique can be used in the series-parallel case.

3.5 LINEARITY DEVIATION

To calibrate the SR 1010 as a voltage divider we need to know the difference between the actual ratio of the output to input voltages and the setting. This difference is called linearity deviation.

$$L = \frac{E_{out}}{E_{in}} - S$$

L - linearity deviation

E_{in} - actual input voltage

E_{out} - actual output voltage

S - divider setting

Since the voltage and resistance divide proportionately, the linearity deviation can be found by a precision comparison of the resistors in the divider string. By using ten resistors of the SR 1010 in the divider string, the output can be set to integral multiples of a tenth the input voltage. The linearity deviation for this divider can be written as:

$$L = \frac{\sum_{n=1}^{10S} R_n}{\sum_{n=1}^{10} R_n} - S$$

L - linearity deviation

R_n - resistance of nth resistor

$\sum_{n=1}^{10S} R_n$ - resistance from COM to OUT in ohms

$\sum_{n=1}^{10} R_n$ - total input resistance in ohms

S - divider setting

If all of the resistors in the string were equal, the voltage would divide equally. To find how far from the ideal this divider is each resistor, R_n, of the string is compared to a standard resistor. To maintain the ultimate in measurement accuracy four-terminal measurements should be made. The measured resistance deviation is used to calculate the linearity deviation.

$$R_n = R_s (1 + d_n)$$

R_n = resistance of nth resistor in ohms

R_s = resistance of standard resistor in ohms

d_n = per unit deviation of R_n from R_s

This leads to the following expression for linearity deviation:

$$L = \frac{\sum_{n=1}^{10S} (1 + d_n)}{\sum_{n=1}^{10} (1 + d_n)} - S$$

The precise value of the standard resistor is unimportant since it is canceled out of the equation, thus anyone of the resistors of the string can be used as the standard resistor. To simplify calculations the equation for linearity deviation can be modified by first defining the average deviation as $d_{av}^{10} = 0.1 \sum_{n=1}^{10} d_n$ and then assuming d_{av}^{10} is much smaller than one. The equation for linearity deviation can then be expressed as follows:

$$L = 0.1 \sum_{n=1}^{10S} (d_n - d_{av}^{10})$$

SECTION IV
CALIBRATION

4.1 INTRODUCTION

This section provides MODEL SR 1010 TRANSFER STANDARD calibration procedures for those that have the necessary facilities. Calibration should be performed in a laboratory environment. If this is not possible return the instrument to the factory or an authorized service facility for calibration.

Calibration of the SR 1010 for immediate use at highest accuracy is a part of the normal operating procedure, the detailed procedures are given in Section II. This section will contain comments related to systematic or routine calibration, and to special tests. These procedures will verify the performance of the whole SR 1010 calibration system, including the SB 103 SHORTING BARS, the PC 101 PARALLEL COMPENSATION NETWORK and SPC 102 SERIES-PARALLEL COMPENSATION NETWORK.

4.2 EQUIPMENT REQUIRED

1) Resistance reference standard: Preferably a Thomas pattern one ohm certified to at least 5 ppm.

2) Oil bath: Temperature regulated at certificate temperature of resistance standard or if temperature coefficient of the standard is known a thermometer with 0.1 °C steps for accurately determining the temperature of the oil bath can be used.

3) Comparison bridge: One to one Kelvin comparison bridge or direct reading ratio set for making four-terminal resistance comparisons. The resolution of the bridge and sensitivity of the associated detector should be sufficient to resolve 1 ppm deviations of the unknown from the standard for resistances from 1 ohm to 1 megohm. The short term stability should be better than 1 ppm. (ESI MODEL 240 KELVIN RATIO BRIDGE or equivalent).

4) Environmental requirements:

   Temperature: 23 °C ±1 °C
   Relative humidity: less than 60%, approximately 50%

5) Accessories:

   Shorting bars: paralleling straps for connecting ten resistors in parallel or nine in series-parallel. (ESI MODEL SB 103 or equivalent).
   Compensation networks: networks for making four-terminal parallel and series-parallel connections. (ESI MODELS PC 101 and SPC 102 or equivalent).

6) Microvoltmeter: With an input resistance of at least ten kilohms and on which less than one microvolt can be observed. (ESI MODEL 800 DC GENERATOR-DETECTOR recommended). A galvanometer can be used instead but it may be necessary to calibrate its sensitivity.

7) Current source: Approximately one amp current source; generator of ESI MODEL 800 can be used.

8) Voltage source: Approximately one hundred volt source; generator of ESI MODEL 800 can be used.

4.3 SEQUENCE OF CALIBRATION

4.3.1 CALIBRATION OF AVERAGE OF RESISTOR GROUPS

1) Connect the Thomas pattern one ohm standard resistor to the standard terminals of the comparison bridge. See Figure 4.3.1a.

2) Connect nine resistors of the one ohm per step box in series-parallel using the series-parallel compensation network. See Section 2.2.3 for proper series-parallel connections.

3) Connect these nine series-parallel resistors to the unknown terminals of the bridge. See Figure 4.3.1a.

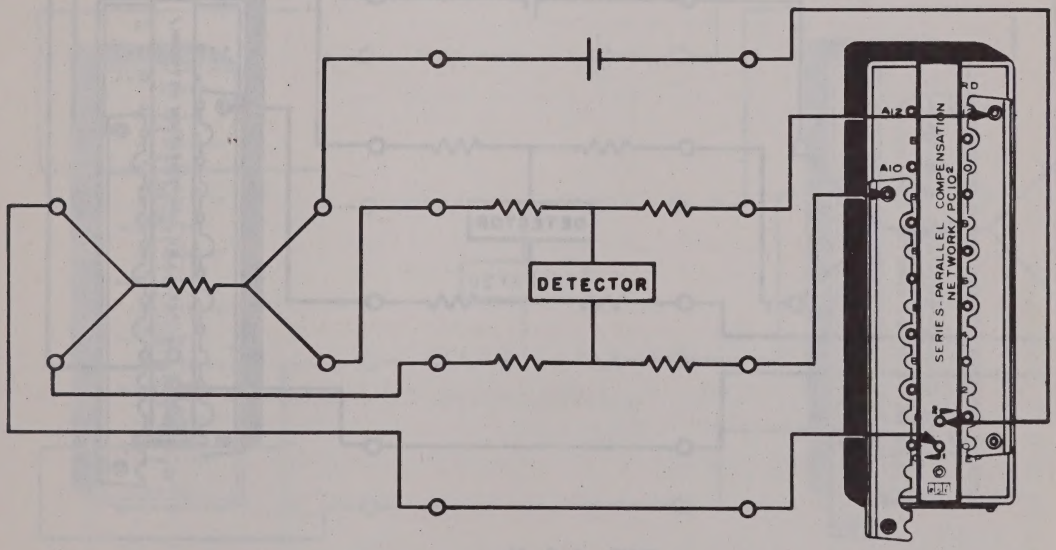


FIG. 4.3.1a

4)	Compare the two resistances by the interchange method described in Section 2.3.2, also see the suggestions given in Section 2.3.3.	This gives the deviation of the one ohm per step SR 1010 from the standard, to find its deviation from nominal add to this the deviation from nominal of the one ohm standard.
5)	Connect the Thomas pattern one ohm standard to the standard terminals of the bridge.	See Figure 4.3.1b.
6)	Connect ten resistors of the ten ohm per step box in parallel using the parallel compensation network and shorting bars.	See Section 2.2.2 for proper parallel connections.

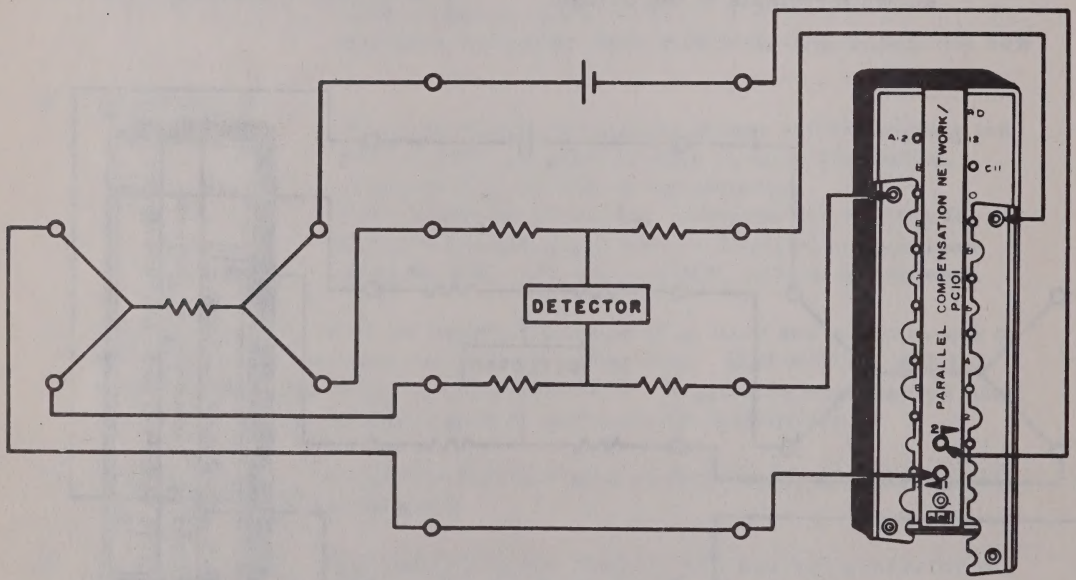


FIG. 4.3.1b

7) Connect the ten parallel resistors of the ten ohm per step box to the unknown terminals of the bridge.

See Figure 4.3.1b.

8) Compare the two resistances by the interchange method described in Section 2.3.2.

This gives the deviation of the ten ohm per step SR 1010 from the standard, to find its deviation from nominal add to this the deviation from nominal of the one ohm standard.

9) Remove the parallel straps from the ten ohm per step box and connect the same ten resistors in series to the standard terminals of the bridge.

See Figure 4.3.1c.

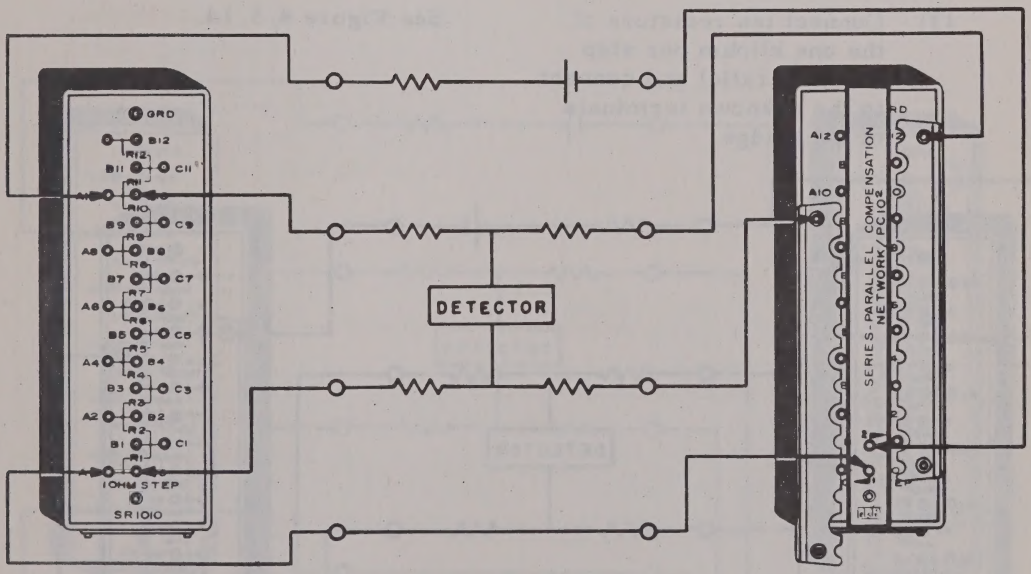


FIG. 4.3.1c

10) Connect nine resistors of the 100 ohm per step box in series-parallel using the compensation network and connect to the unknown terminals of the bridge.

See Section 2.2.3 for proper series-parallel connections and Figure 4.3.1c for connections to bridge.

11) Compare the two resistances by the interchange method described in Section 2.3.2.

This gives the deviation of the one hundred ohm per step box from the ten ohm per step box, to find its deviation from nominal add to this the deviation from nominal of the ten ohm per step box as determined in step 8 above.

12) Connect the ten series connected resistors of the ten ohm per step box to the standard terminals of the bridge.

See Figure 4.3.1d.

13) Connect ten resistors of the one kilohm per step box in parallel and connect to the unknown terminals of the bridge.

See Figure 4.3.1d.

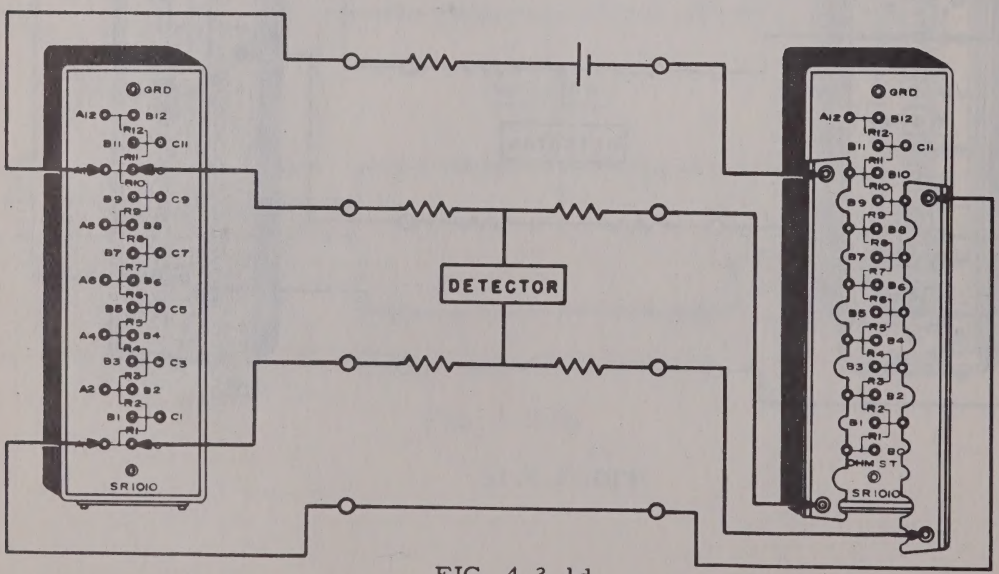


FIG. 4.3.1d

14) Compare the two resistances by the interchange method described in Section 2.3.2.

This gives the deviation of the one kilohm per step box from the ten ohm per step box, to find its deviation from nominal add to this the deviation from nominal of the ten ohm per step box as determined in step 8 above.

15) Remove the parallel straps from the one kilohm per step box and connect the same ten resistors in series to the standard terminals of the bridge.

See Figure 4.3.1e.

16) Connect nine resistors of the ten kilohm per step box in series-parallel and connect to the unknown terminals of the bridge.

See Figure 4.3.1e.

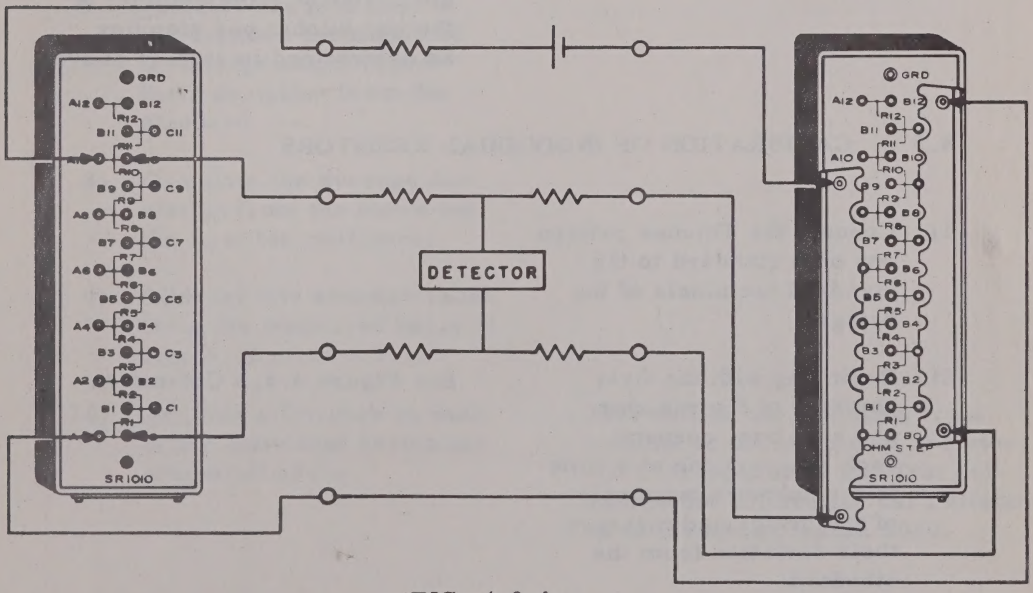


FIG. 4.3.1e

17) Compare the two resistances by the interchange method described in Section 2.3.2.

This gives the deviation of the ten kilohm per step box from the one kilohm per step box, to find its deviation from nominal add to this the deviation from nominal of the one kilohm per step box as determined in step 14 above.

18) Connect the ten series connected one kilohm resistors to the standard terminals of the bridge.

See Figure 4.3.1d.

19) Connect ten resistors of the one hundred kilohm per step box in parallel and connect to the unknown terminals of the bridge.

See Figure 4.3.1d.

20) Compare the two resistances by the interchange method described in Section 2.3.2.

This gives the deviation of the one hundred kilohm per step box from the one kilohm per step box, to find its deviation from nominal add to this the deviation from nominal of the one kilohm per step box as determined in step 14 above.

4.3.2 CALIBRATION OF INDIVIDUAL RESISTORS

1) Connect the Thomas pattern one ohm standard to the standard terminals of the bridge.

2) Beginning with the first resistor of the one ohm per step box, connect each resistor one at a time to the unknown terminals of the bridge and measure their deviation from the standard.

See Figure 4.3.3 Column A.

3)	Calculate the average deviation, from the above, for the first nine resistors.	See Section 4.3.3.
4)	Subtract this average value from the measured value of step 4, Section 4.3.1.	
5)	Add this difference to each of the individual deviations measured above.	This will be the deviation from nominal of the individual resistors, and corresponds to the first column of the calibration card attached to the end of the SR 1010.
6)	Connect the first ten resistors of the one ohm per step box in series to the standard terminals of the bridge.	
7)	Beginning with the first resistor of the ten ohm per step box, connect each resistor one at a time to the unknown terminals of the bridge and measure their deviation from the standard.	
8)	Calculate the average deviation from the above for the first ten resistors.	
9)	Subtract this average value from the measured value of step 8, Section 4.3.1.	
10)	Add this difference to each of the individual deviations measured above.	This will be the deviation from nominal of the individual resistors, and corresponds to the first column of the calibration card attached to the end of the SR 1010.

11) Connect the first ten resistors of the ten ohm per step box in series to the standard terminals of the bridge.

12) Beginning with the first resistor of the one hundred ohm per step box, connect each resistor one at a time to the unknown terminals of the bridge and measure their deviation from the standard.

13) Calculate the average deviation from the above for the first nine resistors.

14) Subtract this average value from the measured value of step 11, Section 4.3.1.

15) Add this difference to each of the individual deviations measured above.

This will be the deviation from nominal of the individual resistors, and corresponds to the first column of the calibration card attached to the end of the SR 1010.

16) Connect the first ten resistors of the one hundred ohm per step box in series to the standard terminals of the bridge.

17) Beginning with the first resistor of the one kilohm per step box, connect each resistor one at a time to the unknown terminals of the bridge and measure their deviation from the standard.

18) Calculate the average deviation from the above for the first ten resistors.

19) Subtract this average value from the measured value of step 14, Section 4.3.1.

20) Add this difference to each of the individual deviations measured above.

This will be the deviation from nominal of the individual resistors, and corresponds to the first column of the calibration card attached to the end of the SR 1010.

21) Connect the first ten resistors of the one kilohm per step box in series to the standard terminals of the bridge.

22) Beginning with the first resistor of the ten kilohm per step box, connect each resistor one at a time to the unknown terminals of the bridge and measure their deviation from the standard.

23) Calculate the average deviation from the above for the first nine resistors.

24) Subtract this average value from the measured value of step 17, Section 4.3.1.

25) Add this difference to each of the individual deviations measured above.

This will be the deviation from nominal of the individual resistors, and corresponds to the first column of the calibration card attached to the end of the SR 1010.

26) Connect the first ten resistors of the ten kilohm per step box in series to the standard terminals of the bridge.

27) Beginning with the first resistor of the one hundred kilohm per step box, connect each resistor one at a time to the unknown terminals of the bridge and measure their deviation from the standard.

28) Calculate the average deviation from the above for the first ten resistors.

29) Subtract this average value from the measured value of step 20, Section 4.3.1.

30) Add this difference to each of the individual deviations measured above.

This will be the deviation from nominal of the individual resistors, and corresponds to the first column of the calibration card attached to the end of the SR 1010.

Compare these calibrated values with those on the chart at the end of the boxes. Before replacing this chart with one using the values just determined be sure that the standards and procedures used in the new calibration were sufficiently accurate. It is also recommended that the charts not be replaced unless two or more complete calibration sequences give the same answer, preferably when performed by different operators, and even using different bridges or ratio sets if available.

4.3.3 FILLING OUT THE CALIBRATION CARD

If it has been determined that the values given on the calibration card are no longer correct the following procedure is recommended for filling out a new card.

1)	List the deviation from nominal of the individual resistors as measured in Section 4.3.2.	See Figure 4.3.3 Column A.
2)	Calculate the group average from these deviations corresponding to the group average measured in Section 4.3.1.	This group will consist of the first nine resistors for the 1 ohm, 100 ohm and 10 kilohm per step boxes and the first ten resistors for the 10 ohm, 1 kilohm and 100 kilohm per step boxes.
3)	Subtract the calculated average from the measured average to obtain the correction for the measured individual deviations.	
4)	Add the above correction to each of the measured individual deviations.	See Figure 4.3.3 Column B.
5)	Sum up each of the individual deviations from the first down to each of the subsequent deviations. For example, the cumulative sum corresponding to R4 will be the sum of the deviations of R1, R2, R3, and R4.	See Figure 4.3.3 Column C.
6)	Divide each of the cumulative sums by the number of deviations involved in the sum. For example, the cumulative sum corresponding to R4 will be divided by four.	See Figure 4.3.3 Column D.
7)	Round off the corrected individual deviations to the nearest ppm and fill in the first column of the calibration chart (labeled Individual (ppm)) with these values.	See Figure 4.3.3 sample calibration chart.

8) Round off the cumulative averages to the nearest ppm and fill in the second column of the calibration chart (labeled Cumulative (ppm)) with these values.

See Figure 4.3.3 sample calibration chart.

	A Measured Individual Deviations (From Section 4.3.2)	B Corrected Individual Deviations	C Cumulative Sum	D Cumulative Average
R1	+3.6	+2.1	+2.1	+2.1
R2	+5.7	+4.2	+6.3	+3.2
R3	+0.3	-1.2	+5.1	+1.7
R4	+5.3	+3.8	+8.9	+2.2
R5	-1.6	-3.1	+5.8	+1.2
R6	+4.9	+3.4	+9.2	+1.5
R7	+4.5	+3.0	+12.2	+1.7
R8	-3.2	-4.7	+7.5	+0.9
R9	+4.0	+2.5	+10.0	+1.1
R10	+6.6	+5.1	+15.1	+1.5
R11	+3.2	+1.7	+16.8	+1.5
R12	-2.7	-4.2	+12.6	+1.0

9 | 23.5 Sum
2.6 Average

Measured group average for nine resistors (From Section 4.3.1) = +1.1

Minus group average calculated from measured individual deviations = -2.6

Correction to be added to measured individual deviations = -1.5

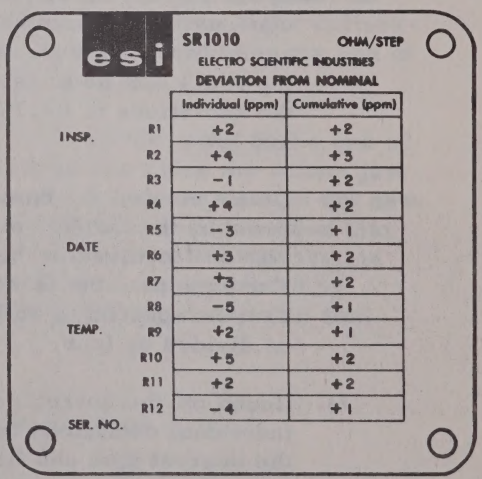


FIG. 4.3.3

4.4 SPECIAL TESTS

4.4.1 JUNCTION TRANSRESISTANCE

An essential characteristic of the ESI MODEL SR 1010 TRANSFER STANDARDS is the low resistance of the junction between the resistors and the binding posts (less than one microhm). If the junction transresistance is too high, the transfer accuracy of the units will be impaired.

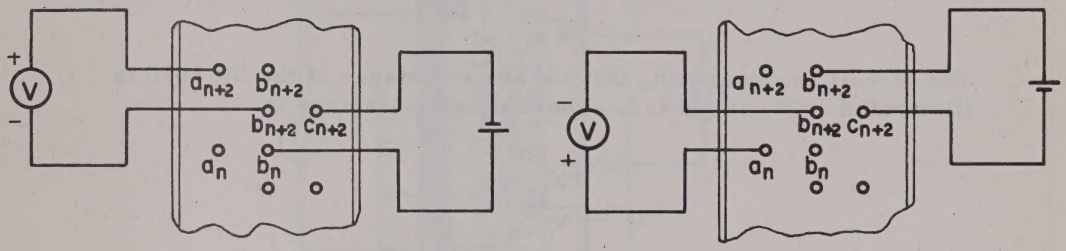
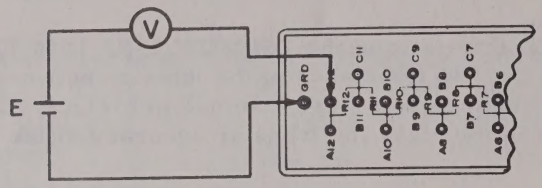


FIG. 4.4.1

The method of checking the junction transresistance is illustrated in Figure 4.4.1. By using a current source of one amp and a microvoltmeter capable of seeing one tenth of a microvolt the junction resistance can be measured to a tenth of a microhm. The transresistance measured by both the circuits shown and their difference should be less than 1/2 microhm. This test need be made on the one ohm per step and ten ohm per step boxes only, since the resistance of the junction material is too small to cause as much as one ppm error in a one hundred ohm per step box.

4.4.2 INSULATION RESISTANCE



The circuit for measuring the leakage resistance of the SR 1010 is illustrated in Figure 4.4.2. The leakage resistance is:

$$R_L = \frac{ER_M}{V}$$

where:

R_L is the leakage resistance from all terminals in parallel to ground in ohms.
E is the supply voltage in volts.
R_M is the input resistance of the meter.
V is the reading of the voltmeter.

R_L should be greater than 10^{12} ohms.

4.4.3 FOUR-TERMINAL PARALLELING ACCURACY OF THE SYSTEM

The uncertainty due to connection resistances of four terminal resistors in parallel is less than:

$$\pm 2\left(\frac{r}{R}\right)(d_{CR} - d_R)$$

where:

r is the greatest bus bar resistance.
R is the nominal value of the resistors being paralleled.
$(d_{CR} - d_R)$ is the greatest bridge unbalance in terms of the compensation resistors and the resistors being connected.

The values of $\frac{r}{R}$ and $(d_{CR} - d_R)$ can be measured to find the expected accuracy of a particular connection.

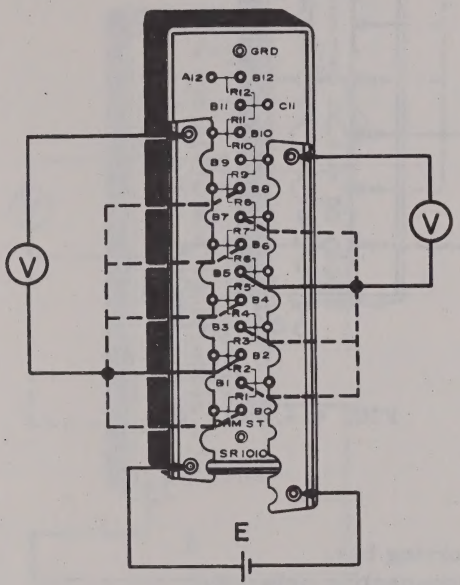


FIG. 4.4.3a

The value of $\frac{r}{R}$ can be found by measuring the voltage drops from a point on the bus bars to the junction of adjacent resistors, shown in Figure 4.4.3a.

1) Connect the shorting bar.
2) Measure voltage from a point on the bars to the unused terminals, this is the voltage to the junction of adjacent resistors.
3) Find the maximum difference of values V for each bar.
4) Use the greatest V difference to calculate $(\frac{r}{R})_{max}$

$$\frac{V_{max} - V_{min}}{E} = (\frac{r}{R})_{max}$$

The bridge unbalance can be measured as shown in Figure 4.4.3b. The measured values can be multiplied together and doubled to give an upper bound of the connection error. This usually includes a very substantial safety factor.

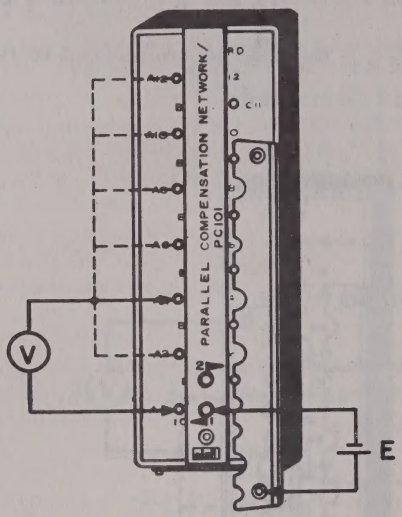


FIG. 4.4.3b

1) Connect one shorting bar.
2) Connect the compensating network.
3) Supply a voltage E from the shorting bar to the other side of the network.
4) Measure the voltage V from one unused shorting bar terminal to each of the others.
5) Change the shorting bar to the other side and repeat.
6) Find the maximum voltage difference $(V_{max} - V_{min})$ between terminals.
7) Calculate $(d_{CR} - d_R)_{max}$

$$\left(\frac{V_{max} - V_{min}}{E}\right)\left(2 + \frac{2R_0}{R} + \frac{R}{R_0}\right) = (d_{CR} - d_R)_{max}$$

4.4.4 FOUR-TERMINAL SERIES-PARALLELING ACCURACY OF THE SYSTEM

The determination of the four-terminal series-parallel accuracy is the same as that of the four-terminal parallel accuracy described in Section 4.4.3. See Figure 4.4.4a for measuring $\frac{r}{R}$ and 4.4.4b for measuring $(d_{CR} - d_R)$.

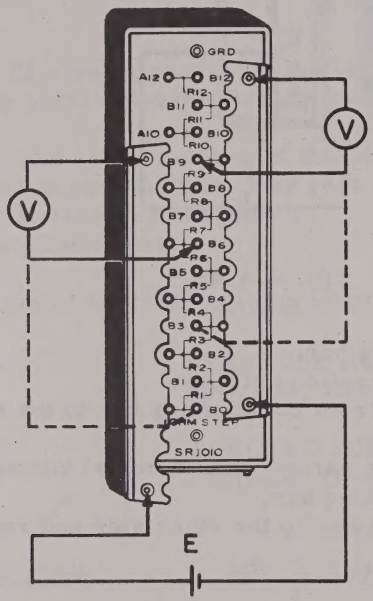


FIG. 4.4.4a

1) Connect the shorting bars.
2) Measure the voltage from a point on the bars to the terminals that would normally be connected to the compensation network.
3) Find the maximum difference of values V for each bar.
4) Use the greatest V difference to calculate $(\frac{r}{R})_{max}$

$$\frac{V_{max} - V_{min}}{E} = (\frac{r}{R})_{max}$$

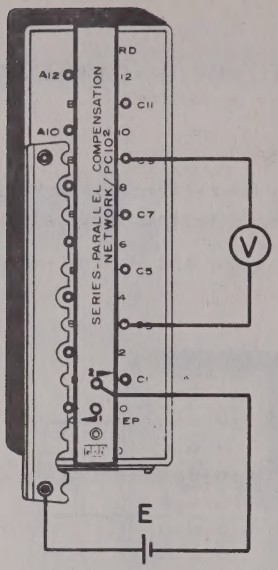


FIG. 4.4.4b

1) Connect the shorting bar.
2) Connect the compensation network.
3) Supply a voltage E from the shorting bar to the other side of the network.
4) Measure the voltage between the terminal normally connected to the missing shorting bar.
5) Change the shorting bar to the other side and repeat.
6) Calculate $(d_{CR} - d_R)_{max}$.

$$(d_{CR} - d_R) = \left(\frac{V_{max} - V_{min}}{E}\right)\left(2 + \frac{2CR}{3R} + \frac{3R}{CR}\right)$$

where:

R is the nominal value of the resistors of the SR 1010.
CR is the nominal value of the resistors in the compensation network.

SECTION V

PARTS LIST

Manufacturer of the part is given in a code number according to the Federal Supply Code for Manufacturers; see list of manufacturers below. Parts recommended as spares to sustain operation in isolated locations are indicated in the recommended spare parts column.

Parts manufactured by Electro Scientific Industries must be ordered from the factory. When ordering parts from the factory include the following information:

Model and serial number of the instrument
Electro Scientific Industries part number
Circuit reference designator
Description of part

CODE LIST OF MANUFACTURERS

11702	SYRACUSE RUBBER PRODUCTS COMPANY Syracuse, New York
11837	ELECTRO SCIENTIFIC INDUSTRIES Portland, Oregon

Description	Mfr	ESI Part No.	Qty Used	Recm SP
Cap, Binding Post, Metal	11837	1172	2	2
Cap, Binding Post, Ins.	11837	1170	26	12
Bumper, Rubber Mfr PN M-266	11702	8220	4	2
Holder, Card	11837	8535	1	1
Card, Calibration	11837	8536	1	5